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## Neutrino Fluxes from Active Galaxies: a Model-Independent Estimate

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There are tantalizing hints that jets, powered by supermassive black holes at the center of active galaxies, are true cosmic proton accelerators. They produce photons of TeV energy, possibly higher, and may be the enigmatic source of the highest energy cosmic rays. Photoproduction of neutral pions by accelerated protons on UV light is the source of the highest energy photons, in which most of the bolometric luminosity of the galaxy may be emitted. The case that proton beams power active galaxies is, however, far from conclusive. Neutrinos from the decay of charged pions represent an uncontroversial signature for the proton induced cascades. We show that their flux can be estimated by model-independent methods, based on dimensional analysis and textbook particle physics. Our calculations also demonstrate why different models for the proton blazar yield very similar results for the neutrino flux, consistent with the ones obtained here.

### Introduction

In recent years cosmic ray experiments have revealed the existence of cosmic particles with energies in excess of  $10^{20}$  eV. Incredibly, we have no clue where they come from and how they have been accelerated to this energy[1]. The highest energy cosmic rays are, almost certainly, of extra-galactic origin. Searching the sky beyond our galaxy, the nuclei of active galaxies (AGN) stand out as the most likely sites of magnetic fields which are sufficiently strong and expansive to accelerate particles to joules of energy. The idea is rather compelling because AGN are also the source of the highest energy photons, detected with air Cherenkov telescopes[2].

AGN are the brightest sources in the Universe. Their engines must not only be powerful, but extremely compact because their high energy luminosities are observed to flare by over an order of magnitude over time periods as short as a day[3]. Only sites in the vicinity of black holes, a billion times more massive than our sun, can possibly

satisfy the constraints of the problem. Highly relativistic and confined jets of particles are a common feature of these objects. It is anticipated that beams, accelerated near the black hole, are dumped on the radiation in the galaxy which consists of mostly thermal photons with densities of order  $10^{14}/\text{cm}^3$ . The multi-wavelength spectrum, from radio waves to TeV gamma rays, is produced in the interactions of the accelerated particles with the magnetic fields and ambient light in the galaxy. In the more conventional electron models, the highest energy photons are produced by Compton scattering of accelerated electrons on thermal UV photons which are scattered from 10 eV up to TeV energy[4]. The energetic gamma rays will subsequently lose energy by electron pair production in photon-photon interactions with the radiation field of the jet or the galactic disk. An electromagnetic cascade is thus initiated which, via pair production on the magnetic field and photon-photon interactions, determines the emerging gamma-ray spectrum at lower energies. The lower energy photons, observed by conventional astronomical techniques, are, as a result of the cascade process, several generations removed from the primary high energy beams.

The EGRET instrument on the Compton Gamma Ray Observatory has detected high energy gamma-ray emission, in the range 20 MeV–30 GeV, from over 100 sources[5]. Of these sources 16 have been tentatively, and 42 solidly identified with radio counterparts. All belong to the “blazar” subclass, mostly Flat Spectrum Radio Quasars, while the rest are BL-Lac objects[6]. In a unified scheme of AGN, they correspond to Radio Loud AGN viewed from a position illuminated by the cone of a relativistic jet[7]. Moreover of the five TeV gamma-ray emitters identified by the air Cherenkov technique, three are extra-galactic and are also nearby BL-Lac objects[2]. The data therefore strongly suggests that the highest energy photons originate in jets beamed to the observer. Several of the sources observed by EGRET have shown strong variability, by a factor of 2 or so over a time scale of several days[3]. Time variability is more spectacular at higher energies. On May 7, 1996 the Whipple telescope observed an increase of the TeV-emission from the blazar Markarian 421 by a factor 2 in 1 hour reaching, eventually, a value 50 times larger than the steady flux. At this point the telescope registered 6 times more photons from the Markarian blazar, more distant by a factor  $10^5$ , than from the Crab supernova remnant[8].

Does pion photoproduction by accelerated protons play a central role in blazar jets? This question has been extensively debated in recent years[9]. If protons are accelerated along with electrons, they will acquire higher energies, reaching PeV–EeV energy because of reduced energy losses. High energy photons result from proton-induced photoproduction of neutral pions on the ubiquitous UV thermal background. Accelerated protons thus initiate a cascade which dictates the features of the spectrum at lower energy[10]. From a theorist’s point of view the proton blazar has attractive features. Protons, unlike electrons, efficiently transfer energy from the black hole in the presence of the high magnetic fields required to explain the confinement of the jets[11]. Protons provide a “natural” mechanism for energy transfer from the central engine over distances as large as 1 parsec, as well as for the observed heating of the

dusty disk over distances of several hundred parsecs[10]. More to the point, the issue of proton acceleration can be settled experimentally because the proton blazar is a source of high energy protons and neutrinos, not just gamma rays[12].

Weakly interacting neutrinos can, unlike high energy gamma-rays and high energy cosmic rays, reach us from more distant and much more powerful AGN. It is likely that absorption effects explain why Markarian 421, the closest blazar on the EGRET list at a distance of  $\sim 150$  Mpc, produces the most prominent TeV signal. Although the closest, it is one of the weakest; the reason that it is detected whereas other, more distant, but more powerful, AGN are not, must be that the TeV gamma rays suffer absorption in intergalactic space by interaction with background infra-red light[13]. This most likely provides the explanation why much more powerful quasars with significant high energy components such as 3C279 at a redshift of 0.54 have not been identified as TeV sources. Undoubtedly, part of the TeV flux is also absorbed on the infrared light in the source; we will return to this further on.

## 1. Modelling of Blazar Jets

First order Fermi acceleration offers a very attractive model for acceleration in jets, providing, on average, the right power and spectral shape. A cosmic accelerator in which the dominant mechanism is first order diffusive shock acceleration, will indeed produce a spectrum

$$dN/dE \propto E^{-\gamma},$$

with  $\gamma \sim 2 + \epsilon$ , where  $\epsilon$  is a small number. For strong ultra-relativistic shocks it can be negative ( $\sim -0.3$ ). Confronted with the challenge of explaining a relatively flat multi-wavelength photon emission spectrum which extends to TeV energy, models have converged on the blazar blueprint shown in Fig. 1. Particles are accelerated by Fermi shocks in bunches of matter travelling along the jet with a bulk Lorentz factor of order  $\gamma \sim 10$ . Ultra-relativistic beaming with this Lorentz factor provides the natural interpretation of the observed superluminal speeds of radio structures in the jet[14]. In order to accommodate bursts lasting a day in the observer's frame, the bunch size must be of order  $\Gamma c \Delta t \sim 10^{-2}$  parsecs. Here  $\Gamma$  is the Doppler factor, which for observation angles close to the jet direction is of the same order as the Lorentz factor [7]. These bunches are, in fact, more like sheets, thinner than the jet's width of roughly 1 parsec. The observed radiation at all wavelengths is produced by the interaction of the accelerated particles in the sheets with the ambient radiation in the AGN, which has a significant component concentrated in the so-called "UV-bump".

In electron models the multi-wavelength spectrum consists of three components: synchrotron radiation produced by the electron beam on the  $B$ -field in the jet, synchrotron photons Compton scattered to high energy by the electron beam and, finally, UV photons Compton scattered by the electron beam to produce the highest energy photons in the spectrum[4]. The seed photon field can be either external, e.g. radiated off the accretion disk, or result from the synchrotron radiation of the electrons

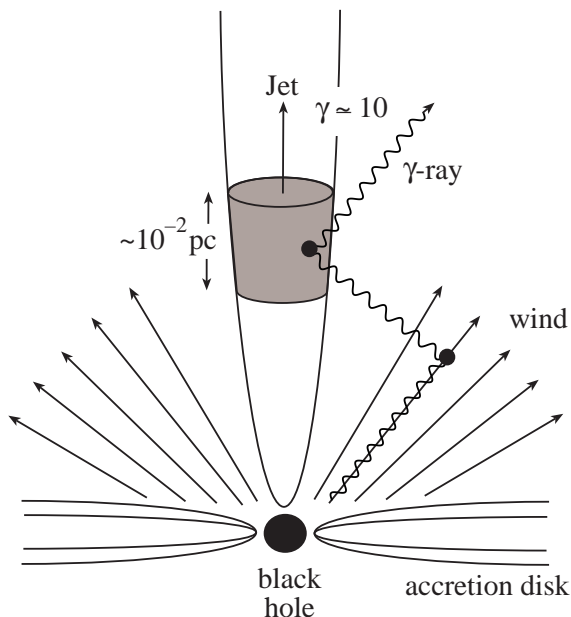


Figure 1: Possible blueprint for the production of high energy photons and neutrinos near the super-massive black hole powering an AGN. Particles, accelerated in sheet like bunches moving along the jet, interact with photons radiated by the accretion disk or produced by the interaction of the accelerated particles with the magnetic field of the jet.

in the jet, so-called synchrotron-self-Compton models. The picture has a variety of problems. In order to reproduce the observed high energy luminosity, the accelerating bunches have to be positioned very close to the black hole. The photon target density is otherwise insufficient for inverse Compton scattering to produce the observed flux. This is a balancing act, because the same dense target will efficiently absorb the high energy photons by  $\gamma\gamma$  collisions. The balance is difficult to arrange, especially in light of observations showing that the high energy photon flux extends beyond TeV energy[2]. The natural cutoff occurs in the 10–100 GeV region[4]. Finally, in order to prevent the electrons from losing too much energy before producing the high energy photons, the magnetic field in the jet has to be artificially adjusted to less than 10% of what is expected from equipartition with the radiation density.

For these, and the more general reasons already mentioned in the introduction, the proton blazar has been developed. In this model protons as well as electrons are accelerated. Because of reduced energy loss, protons can produce the high energy radiation further from the black hole. The more favorable production-absorption balance far from the black hole makes it relatively easy to extend the high energy photon spectrum above 10 TeV energy, even with bulk Lorentz factors that are significantly smaller than in the inverse Compton models. Two recent incarnations of the proton blazar illustrate that these models can also describe the multi-wavelength spectrum

of the AGN[15, 16]. Because the seed density of photons is still much higher than that of target protons, the high energy cascade is initiated by the photoproduction of neutral pions by accelerated protons on ambient light via the  $\Delta$  resonance. The protons collide either with synchrotron photons produced by electrons[15], or with the photons radiated off the accretion disk[16], as shown in Fig. 1.

## 2. The Neutrino Flux from Blazar Jets

Model-independent evidence that AGN are indeed cosmic proton accelerators can be obtained by observing high energy neutrinos from the decay of charged pions, photoproduced on the  $\Delta$  resonance along with the neutral ones. The expected neutrino flux can be estimated in six easy steps.

1. The size of the accelerator  $R$  is determined by the duration, of order 1 day, over which the high energy radiation is emitted:

$$R = \Gamma t c = 10^{-2} \text{ parsecs for } t = 1 \text{ day.} \quad (1)$$

2. The magnitude of the  $B$ -field can be calculated from equipartition with the electrons, whose energy density is measured experimentally:

$$\frac{B^2}{2\mu_0} = \rho(\text{electrons}) \sim 1 \text{ erg/cm}^3. \quad (2)$$

This yields a value for the magnetic field of 5 Gauss. A similar value is obtained by scaling  $B$ -fields in the jets of Fannaroff-Riley type II galaxies at kiloparsec distances, to the Markarian 421 luminosity, and to transverse distances in the milliparsec range[11].

3. In shock acceleration the gain in energy occurs gradually as a particle near the shock scatters back and forth across the front gaining energy with each transit. The proton energy is limited by the lifetime of the accelerator and the maximum size of the emitting region,  $R$ [12]

$$E < KZeBRc. \quad (3)$$

Here  $Ze$  is the charge of the particle being accelerated and  $B$  the ambient magnetic field. The upper limit basically follows from dimensional analysis. It can also be derived from the simple requirement that the gyroradius of the accelerated particles must be contained within the accelerating region  $R$ . The numerical constant  $K \sim 0.1$  depends on the details of diffusion in the vicinity of the shock, which determine the efficiency by which power in the shock is converted into acceleration of particles. In some cases it can reach values close to 1. The maximum energy reached is

$$E_{\text{max}} = eBRc = 5 \times 10^{19} \text{ eV}$$

for  $B = 5$  Gauss and  $R = 0.02$  parsecs. We here assumed that the boost of the energy in the observer's frame approximately compensates for the efficiency factor, i.e.  $K\Gamma \sim 1$ .

The neutrino energy is lower by two factors which take into account i) the average momentum carried by the secondary pions relative to the parent proton ( $\langle x_F \rangle \simeq 0.2$ ) and ii) the average energy carried by the neutrino in the decay chain  $\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ , which is roughly 1/4 of the pion energy because equal amounts of energy are carried by the four leptons. The maximum neutrino energy is

$$E_{\nu \max} = E_{\max} \langle x_F \rangle \frac{1}{4} \simeq 10^{18} \text{ eV}, \quad (4)$$

i.e. neutrinos reach energies of  $10^3$  PeV.

4. The neutrino spectrum can now be calculated from the observed gamma ray luminosity. We recall that approximately equal amounts of energy are carried by the four leptons that result from the decay chain  $\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ . In addition the cross sections for the processes  $p\gamma \rightarrow p\pi^0$  and  $p\gamma \rightarrow n\pi^+$  at the  $\Delta$  resonance are in the approximate ratio of 2 : 1. Thus 3/4 of the energy lost to photoproduction ends up in the electromagnetic cascade and 1/4 goes to neutrinos, which corresponds to a ratio of neutrino to gamma luminosities ( $L_\nu : L_\gamma$ ) of 1 : 3. This ratio is somewhat reduced when taking into account that some of the energy of the accelerated protons is lost to direct pair production ( $p + \gamma \rightarrow e^+ e^- p$ ):

$$L_\nu = \frac{3}{13} L_\gamma. \quad (5)$$

In order to convert above relation into a neutrino spectrum we have to fix the spectral index. We will assume that the target photon density spectrum is described by a  $E^{-(1+\alpha)}$  power law, where  $\alpha$  is small for AGN with flat spectra. The number of target photons above photoproduction threshold grows when the proton energy  $E_p$  is increased. If the protons are accelerated to a power law spectrum with spectral index  $\gamma (= 2 + \epsilon)$ , the threshold effect implies that the spectral index of the secondary neutrino flux is also a power law, but with an index flattened by  $(1 + \alpha)$  as a result of the increase in target photons at resonance when the proton energy is increased:

$$\frac{dN_\nu}{dE_\nu} = \mathcal{N} \left[ \frac{E_\nu}{E_{\nu \max}} \right]^{-(1+\epsilon-\alpha)}. \quad (6)$$

For a standard non relativistic shock with  $\epsilon = 0$  and a flat photon target with  $\alpha = 0$ , the neutrino spectrum will flatten by just one unit giving  $E \frac{dN_\nu}{dE} \sim \text{constant}$ . From Eqs. (5) and (6)

$$\int^{E_{\nu \max}} E \frac{dN_\nu}{dE_\nu} dE_\nu \simeq \mathcal{N} \frac{E_{\nu \max}^2}{1 - \epsilon + \alpha} \simeq \frac{3}{13} L_\gamma. \quad (7)$$

The calculation is stable as long as  $\epsilon - \alpha$  is smaller than 1 because the luminosity integral is not sensitive to the lower limit of the integration.

5. Assuming that the high energy  $\gamma$  ray flux from Markarian 421 results from cascading of the gamma ray luminosity produced by Fermi accelerated protons, we obtain the neutrino flux from the measured value[2] of  $L_\gamma$  of  $2 \times 10^{-10} \text{ TeV cm}^{-2} \text{ s}^{-1}$ :

$$\frac{dN_\nu}{dE_\nu} = \frac{3}{13} \frac{L_\gamma}{E_{\nu \text{ max}}} \frac{1 - \epsilon + \alpha}{E_\nu} \left[ \frac{E_\nu}{E_{\nu \text{ max}}} \right]^{-(\epsilon + \alpha)} \sim \frac{5 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1}}{E_\nu}, \quad (8)$$

where the numerical estimate corresponds to  $\alpha = \epsilon = 0$  and the value of  $E_{\nu \text{ max}}$  of Eq. (4). This calculation reveals that for the small values of  $\epsilon$  and  $\alpha$  anticipated, the neutrino flux is essentially determined by the value for  $E_{\nu \text{ max}}$ .

6. In order to calculate the diffuse flux from the observed blazar distribution, we note that the EGRET collaboration has constructed a luminosity function covering the observation of the  $\sim 20$  most energetic blazars and estimated the diffuse gamma ray luminosity[17]. From the ratio of the diffuse gamma ray flux and the flux of Markarian 421, we obtain that the effective number of blazars with Markarian 421 flux is  $\sim 130 \text{ sr}^{-1}$ . The diffuse neutrino flux is now simply estimated by multiplying the calculated flux for Markarian 421 by this factor. A correction for the difference in spectral indices of gamma ray and neutrino fluxes enhances the neutrino flux by a factor of three. The flux corresponds to an energy regime well below the high energy cut-off. The transition to the cutoff should be smooth because of the superposition of the different redshifts and cut-off energies of the individual blazars.

This concludes our calculation. It illustrates how the proton blazar, unlike the electron blazar, requires no large Doppler factors and no fine-tuning of parameters. For the proton blazar, radiation and magnetic fields are in equipartition, the maximum energy matches the  $BR$  value expected from dimensional analysis and, finally, the size of the bunches is similar to the gyroradius of the highest energy protons. It is not a challenge to increase gamma ray energies well beyond the TeV energy range. Reasonable variations of the values of magnetic field strength  $B$ , the efficiency parameter  $K$  and the Doppler boost factor  $\Gamma$  may allow us to account for the highest energy cosmic rays with  $E \sim 3 \cdot 10^{20} \text{ eV}$ .

Also, our calculation demonstrates why models[15, 16] which differ in many aspects, yield very similar predictions for the neutrino flux, consistent with the ones obtained here[18]; this is illustrated in Fig 2.

### 3. The Cosmic Ray Argument

Rather than scaling to the TeV gamma ray flux, we can use the cosmic ray flux at ultra high energies to bracket expectations for the neutrino flux. Models for proton

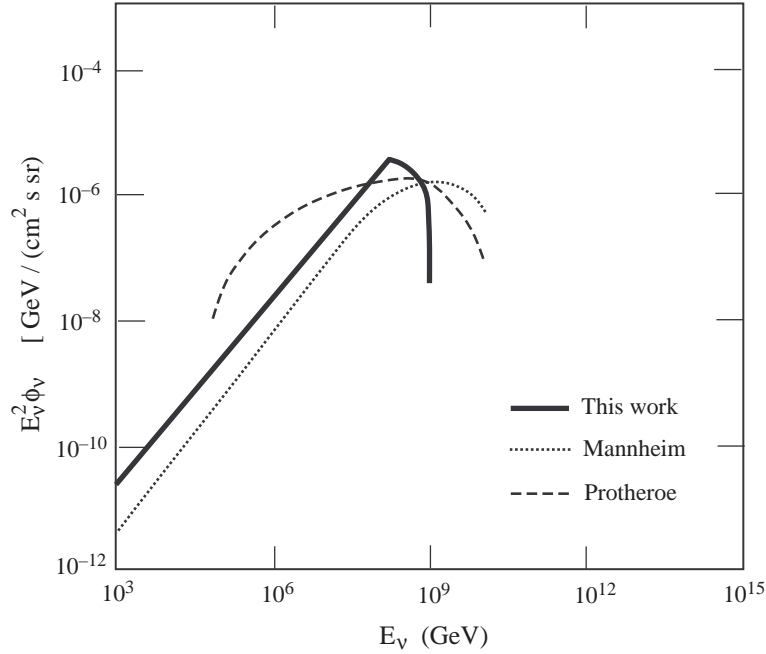


Figure 2: Diffuse neutrino flux from blazars. The numerical result of Equation (8) multiplied by  $3 \times 130 \text{ sr}^{-1}$  and corrected for redshift in the cutoff is compared to recent calculations [15, 16].

acceleration in hot spots of Fanaroff-Riley type II galaxies can explain the observed cosmic ray spectrum above  $\sim 10^{18} \text{ eV}$ [19]. This energy corresponds to the “ankle” in the spectrum, where the observed spectral index flattens from 3 to 2.7. The model requires an  $E^{-2}$ , or flatter, injection spectrum which steepens above  $10^{17} \text{ eV}$  to the observed  $E^{-2.7}$  spectrum as a result of energy loss in the source, interactions with the microwave background, and cosmological evolution[19]. Because of the strict limitations on the density of target photons at the acceleration site, previously discussed, roughly similar neutrino and proton luminosities are expected[12]. In order to understand this balance it is important to realize that in astrophysical beam dumps the accelerator and production target form a symbiotic system. Although larger target density may produce more neutrinos, it also decelerates the protons producing them, in a delicate acceleration-absorption balance. Equal cosmic ray and neutrino luminosity implies:

$$\int dE_\nu (E_\nu dN_\nu/dE_\nu) \sim L_{\text{CR}} \sim 10^{-9} \text{ TeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (9)$$

The bulk cosmic ray luminosity has been conservatively estimated by assuming that it is due to an  $E^{-2.7}$  spectrum above  $\sim 10^{17} \text{ eV}$ . This spectrum has been normalized to the observed EeV cosmic rays. It is interesting to note that this luminosity is a factor 25 below the measured diffuse gamma ray luminosity from AGN[17]. This is,



within an order of magnitude, in agreement with the relation of neutrino and gamma ray luminosities of Eq. (5), and, if anything, implies a conservative estimate of the neutrino flux.

Assuming a generic  $E^{-2}$  neutrino spectrum, the equality of cosmic-ray and neutrino luminosities implies:

$$E_\nu \frac{dN_\nu}{dE_\nu} \sim \frac{10^{-10}}{E_\nu (\text{TeV})} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} . \quad (10)$$

A not too different result is obtained by assuming equal numbers of neutrinos and protons, rather than equal luminosities. It is clear that our estimate is conservative because the proton flux reaching Earth has not been corrected for absorption of protons in ambient matter in the source, or in the interstellar medium.

#### 4. Event Rates in Underground Muon Neutrino Telescopes

The probability to detect a TeV neutrino is roughly  $10^{-6}$ [12]. It is easily computed from the requirement that, in order to be detected, the neutrino has to interact within a distance of the detector which is shorter than the range of the muon it has produced. In other words, in order for the neutrino to be detected, the produced muon has to reach the detector. Therefore,

$$P_{\nu \rightarrow \mu} \simeq \frac{R_\mu}{\lambda_{\text{int}}} \simeq A E_\nu^n , \quad (11)$$

where  $R_\mu$  is the muon range and  $\lambda_{\text{int}}$  the neutrino interaction length. For energies below 1 TeV, where both the range and cross section depend linearly on energy,  $n = 2$ . Between TeV and PeV energies  $n = 0.8$  and  $A = 10^{-6}$ , with  $E$  in TeV units. For EeV energies  $n = 0.47$ ,  $A = 10^{-2}$  with  $E$  in EeV.

We are now ready to compute the diffuse neutrino event rate by folding the neutrino spectrum of Eq. (8) with the detection probability of Eq. (11). We also multiply by  $130 \text{ sr}^{-1}$  for the effective number of sources:

$$\phi^\nu = \int^{E_{\nu \text{ max}}} \frac{dN_\nu}{dE_\nu} P_{\nu \rightarrow \mu}(E_\nu) dE_\nu \simeq 40 \text{ km}^{-2} \text{ year}^{-1} \text{ sr}^{-1} . \quad (12)$$

which implies a yield of two neutrinos every three days in a kilometer-scale detector, assuming only  $2\pi$  coverage.

The steeper, but lower luminosity, flux of Eq. (10) predicts more events when folded with Eq. (11), about  $150 \text{ km}^{-2} \text{ year}^{-1} \text{ sr}^{-1}$  assuming that the flux extends down to TeV energy. The result does not depend strongly on the lower limit of the neutrino integral, it only drops by a factor of three if the neutrino flux flattens below 100 TeV. We again conclude that a kilometer-scale neutrino detector may be required[20]. It is however important to realize that, had we assumed a  $E^{-1}$  spectrum, the resulting

flux would have scaled with the ratio of luminosities to about an order of magnitude below Eq. (12). The energy dependence of the detection efficiency of underground muon neutrino detectors is such that most of the events are detected in the high (low) energy end for a  $E^{-1}$  ( $E^{-2}$ ) spectrum.

## 5. Evidence for the Proton Blazar?

Astronomy with protons becomes possible once their energy has reached a value where their gyroradius in the microgauss galactic field exceeds the dimensions of the galaxy. Provided intergalactic magnetic fields are not too strong, protons with  $10^{20}$  eV energy point at their sources with degree-accuracy. At this energy their mean-free-path in the cosmic microwave background is unfortunately reduced to only tens of megaparsecs. A clear window of opportunity emerges: Are the directions of the cosmic rays with energy in excess of  $\sim 5 \times 10^{19}$  eV correlated to the nearest AGN (red-shift  $z$  less than 0.02), which are known to be clustered in the so-called “super-galactic” plane? Although far from conclusive, there is some evidence that such a correlation may exist[21]. Lack of statistics at the highest energies is a major problem. Future large aperture cosmic ray detectors such as the new Utah HIRES air fluorescence detector and the Auger giant air shower array will soon remedy this aspect of the problem[1].

We have already drawn attention to the 10 TeV maximum photon energy as the demarkation line between the electron and proton blazars. The  $\sim 10$  GeV cutoff in the inverse Compton model can be pushed to the TeV range in order to accommodate the Whipple data on Markarian 421, but not beyond. Bringing the accelerator closer to the black hole may yield photons in excess of 10 TeV energy — they have, however, no chance of escaping without energy loss on the dense infrared background at the acceleration site. HEGRA has been monitoring the 10 closest blazars, including Markarian 421, with its dual telescope systems: the scintillator and the naked photomultiplier detector arrays. The announcement[22] that their upper limit on the photon flux of 50 TeV and above for the aggregate emission from the ten nearest blazars, may be a signal, could provide the first compelling evidence that blazar jets are indeed proton accelerators.

In summary, there are hints that active galaxies may be true particle accelerators with proton beams dictating the features of the spectrum. With the rapidly expanding Baikal and AMANDA detectors producing their first hints of neutrino candidates[23, 24], observation of neutrinos from AGN would establish the production of pions and identify the acceleration of protons as the origin of the highest energy photons. A definite answer may not be known until these detectors reach kilometer size. Neutrino telescope builders should take note that, although smaller neutrino fluxes are predicted than in the generic AGN models of a few years ago[25], they are all near PeV energy where the detection efficiency is increased and the atmospheric neutrino background negligible. Because of the beaming of the jets, the neutrinos have a flatter spectrum peaking near the  $10^6$  TeV maximum energy. The

actual event rates are, in the end, not very different.

If confirmed, these models strongly favor the construction of neutrino telescopes following a distributed architecture, with large spacings of the optical modules and relatively high threshold[20]. This also opens up opportunities for alternative techniques such as the radio technique, or the detection of horizontal air showers with giant air shower arrays[26]. Optimists, on the other hand, can find reasons to anticipate the discovery of AGN neutrinos with much smaller telescopes. With a sufficiently high proton target density in the acceleration region, much larger fluxes of neutrinos may be produced in a proton-proton cascade. The predicted fluxes are however model-dependent[16]. It is also possible, even likely, that accelerated protons which produce neutrinos do not escape the source, or escape after significant energy loss. Such absorption effects increase the neutrino flux relative to the observed high energy cosmic ray flux, also leading to larger neutrino fluxes.

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